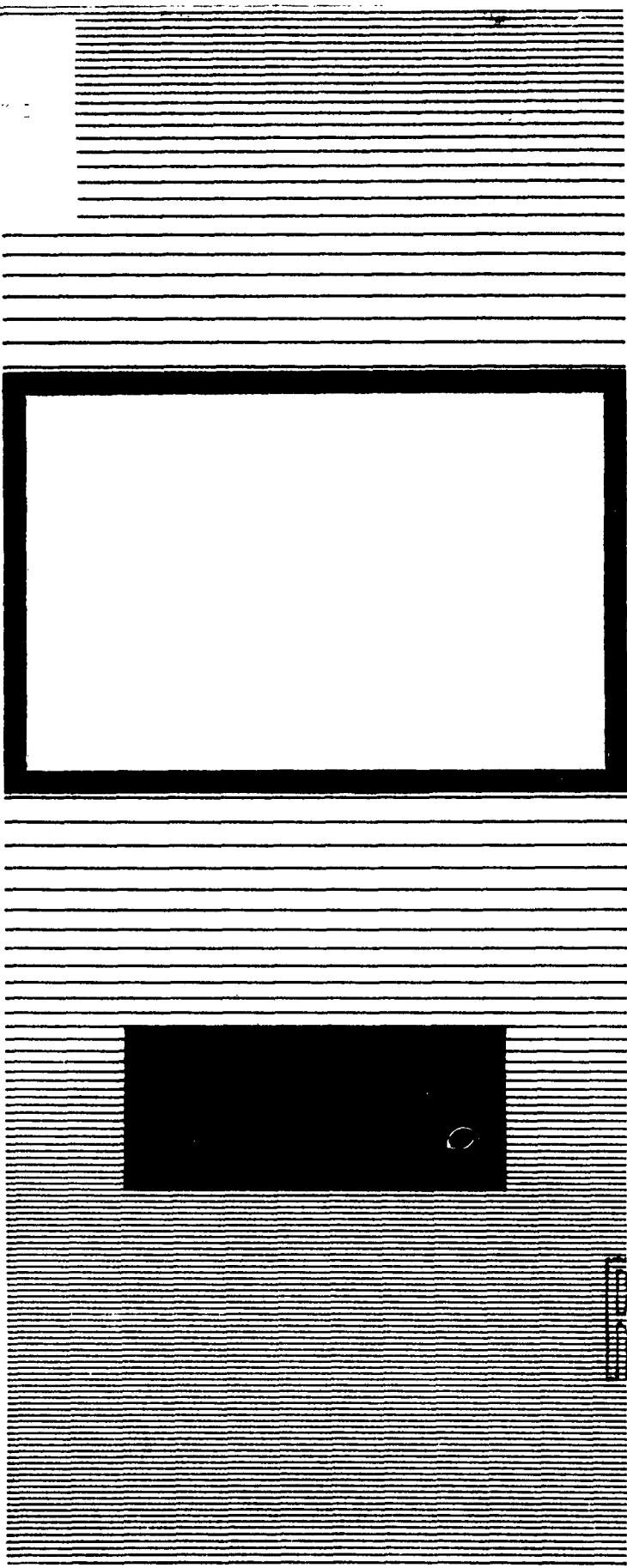


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THE MITRE CORPORATION
P. O. Box 208
Bedford, Massachusetts

AN EXPERIMENTAL STUDY OF CAVITY
COLLAPSE MECHANISM

BY

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ABSTRACT

An experimental investigation was performed to study the mechanism of failure under uniform uniaxial compression of a cube containing a cylindrical hole of a prescribed sectional shape. The load was applied normal to the axis of the hole, and the shapes tested were a circle, an ellipse, a three-quarter circle, and a three-quarter ellipse. The cubes were one foot on a side and the major diameters of the circle and ellipse two inches, the three-quarter shapes being identical to their full counterparts except for the cut-out sections.

The material chosen was plaster of paris and cement mortar. Tests were carried out on three and sometimes four specimens of each type. Detailed notes and photographs were taken of the failure process for each specimen. This information was compiled and summarized and is presented in this report together with a discussion of what was learned and an interpretation of some aspects of the results.

In general the results were found to be consistent within a specimen type and among the types as well. Moreover, the results seem to be at least generally explained on the basis of linear, isotropic elasticity theory and a strength theory in the spirit of Mohr's theory.⁽¹⁾ Some remarks are made concerning the statistical analysis of strength of brittle materials such as plaster with regard to scatter in the data, and reference is made to literature concerned specifically with the properties of plaster.

Comparisons were also made of the failure mode of the circular cavity and those obtained by Rinehart⁽²⁾ under dynamic loadings, and it was found that great similarity exists between the two tests.

Numbers in brackets refer to the bibliography at the end of this report.

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- SR-28, "On the Wave Transmission Between Liquid and Voight Solid," C. C. Mow.
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- SR-34, "Soft Filled Liners for Rock Tunnels in Very High Pressure Environments," Newmark, Hansen and Associates.
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- SR-37, "An Experimental Study of Cavity Collapse Mechanism," Lewis T. Assini, John K. Hawley, and C. C. Mow.
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1.0 INTRODUCTION

This report represents a portion of MITRE's effort concerning the survivability of a deep underground Command and Control installation. Previous studies investigating the ground shock associated with the surface burst of a nuclear weapon have been published (Refs. 3, 4, 5); of particular interest is Ref. 3, which treats the problem of stress wave interaction with a circular cavity. It was found that the magnitude of the dynamic stresses around a circular cavity is essentially the same as is the static case; specifically, the maximum dynamic stress is approximately 10% greater than the static stress. In addition, recent photoelastic studies by AFSWC and ARF⁽⁶⁾ have confirmed these results and have further shown that the dynamic stress concentration factor for other cavity cross-sections (ellipse and square with fillet) can be approximated by the static case.

The static-dynamic stress equivalence discussed above introduces the possibility of experimentally investigating cavity failure mechanisms by the static techniques. Rinehart⁽²⁾ has investigated the collapse mode under impulsive loading of various cavity shapes in plaster of paris and paraffin salt specimens; however, due to the impulsive nature of the loading (explosive charges) it was difficult to measure the actual stress magnitude impinging on the cavity and difficult to determine the sequence of cavity response mechanisms. Hence, this report presents an investigation of the failure under static loading of several cavity shapes in a plaster of paris medium.

The basic purpose of the report is to determine the sequence and type of cavity failure modes and the load level at which they occur. This is accomplished by subjecting cast cube specimens containing cylindrical holes to uniform uniaxial compressive loadings and recording the progress of cavity failure. The hole shapes tested are a circle, an ellipse, a three-quarter circle, and a three-quarter ellipse. The cubes are 12 inches on a side; the diameter of the circle and the major axis of the ellipse are two inches. The ratio of major to minor axes of the ellipse is three to two. The three-quarter circle and ellipse have the same dimensions as their full counterparts, but are truncated on the plane perpendicular to

the diameters at the three-quarter point. The load is applied along the major axis, as this corresponds to the usual cavity orientation.

Sufficient specimens of each type were tested to establish the characteristic fracture mechanism for that hole shape, and any variations in the physical properties of the material among various mixes were recorded from tests on tensile and compressive control samples. During the testing of the specimens, the progress of failure was observed and recorded and photographs were made of significant details.

2.0 PREPARATION OF SPECIMENS

The molds used were fabricated from 1/4 inch steel plates with a machined steel mandrel of the appropriate shape for the hole. They consisted of four parts; the square base plate to which the cylindrical bar was bolted in an upright position and two L-shaped side pieces, which were joined to each other by easily fastened bolt couplings. A pin in the base plate with matching hole in the mandrel assured proper alignment of these two pieces. The sides were heavy enough to require no connection to the base and were made square with respect to the diameter of the mandrel before pouring. Individually tailored wooden trays for each of the four molds further assured proper alignment. All parts of each mold were numbered and were never used interchangeably. The rigidity of the steel plates made four of the surfaces square and flat and leveling the molds before pouring took care of the other two faces. Standard (A.S.T.M.) gang molds were used for the tension and compression samples, the former having a minimum cross-section of one square inch and the latter being cubes two inches on a side. The actual mixing procedure is given in the Appendix; generally the primary concern was for the cleanliness of all the equipment, the strength properties of plaster being considerably effected by dirt, particularly dried plaster. Gold Bond, Quick Set, Super White, Gauging Plaster (National Gypsum Co.) was used. A slow setting type was tried but found unsatisfactory. The water/dry plaster weight ratio found most satisfactory and used for all specimens was 0.54.

When the specimens and samples were poured, they were allowed to dry seven days before testing. They were removed from the molds on the fourth day to dry in the air.

3.0 TEST PROCEDURE

The tests were performed on a TINIUS OLSEN COMPRESSION TESTING machine of 1,200,000 pounds capacity. The top and bottom surfaces of the specimen were coated with "MOBILE-GREASE" to reduce the end effects and care was taken to center them on the base. The ellipse was tested with load parallel to the major axis. The approximate rate of load application was 3,500 to 5,000 pounds per minute or 24.3 to 34.7 pounds per square inch of contact area per minute. Camera and lighting were set up before the loading was begun and two men kept up a constant watch for the appearance of cracks on all sides of the specimen (primarily on the ends and around the edges of the holes). The progress of the failure was recorded with detailed photographs of the surfaces. When the load began to fall steadily and it was obvious from the state of the specimen that its load-carrying capacity was exhausted, the test was terminated.

The control samples (three of each type) were tested immediately, before or after the corresponding specimen. The tension samples were tested in a Riehle machine specifically for the testing of these briquettes; the rate of loading being governed by the steady flow of lead shot out of a balance bucket. This rate of load application was about 200 pounds (psi) per minute. The compression control samples were tested on a Baldwin-Southwark machine using a platform with a spherical seat to assure correct alignment of the cube, and with a loading rate of about 2,400 pounds (600 psi) per minute. The fractures were typical of a brittle material, being pyramidal-shaped or, occasionally, splitting or columnar. The results of the three specimens were averaged to yield the characteristic values for the mix of plaster.

4.0 RESULTS

The test results are summarized in the following table and in the photographs. The first fracture was, in every case, in a vertical plane (or planes for some of the three-quarter specimens where the lower crack did not start in the center of the flat portion of the hole) passing approximately through the major diameter of the hole. The top and bottom cracks appeared simultaneously in all but three cases, and there was only

a slight lag then. This was also the case with regard to the two ends of the hole, although there were more cases in which there was a lag along the length of the hole. In these cases the cracks could be seen to progress along the hole approximately following a generator of the cylinder.

The initiation of the second fracture mode was always observed in the vicinity of the widest part of the hole (the ends of the minor axis of the hole shape). It took the form of a surface crack or a phenomenon within the hole which was given the name "shear wedge", since it consisted of a strip of material along the side of the hole of triangular cross section, which seemed to be forced out by a shearing action accompanying the compression in the region (see Figure 3 & 4). The cracks then went off on a diagonal making an angle with the vertical of somewhat less than 45 degrees.

TABLE I

Fig.No.	Specimen No.	First Fracture Mode lbs. & psi (ffs)*	Second Fracture ^x Mode lbs. & psi (ffs)	Mean Control Sample Data (psi)	Results
1 & 2	C-1	62,400 - 433.3	83,000 - 576.3	Comp. 982 Ten. 148	
3 & 4	C-2	28,000 - 194.4	90,000 - 624.9	Comp. 906 Ten. 199	
5 & 6	C-3	65,000 - 451.3	108,000 - 745.	Comp. 959 Ten. 191	Vertical cracks appeared on front at 83,000. Diagonal cracks go up on both sides, none down.
7 & 8	C-4	56,000 - 388.8	102,000 - 708.3	Comp. 908 Ten. 194	
9 & 10	3/4 C-1	19,000 - 131.9	71,000 - 493.1	Comp. 820 Ten. 180	Interior slippage began at 71,000 went up to 72- dropped to 68- then cracks appeared on outside (not just at plane)
11 & 12	3/4 C-2	60,000 - 416.6	111,000 - 770.8	Comp. 1261 Ten. 219	
13 & 14	3/4 C-3	22,000 - 152.7	24,000 - 166.6	Comp. 1141 Ten. 201	
15 & 16	3/4 C-4	35,000 - 243.0	85,000 - 590.3	Comp. 822 Ten. 228	

^xExcept where noted, ultimate load was not appreciably higher

* Free Field Stress

TABLE II

Fig. No.	Specimen No.	First Fracture Mode lbs. & psi (ffs)*	Second Fracture ^x Mode lbs. & psi (ffs)	Mean Control Sample Data (psi)	Results
17 & 18	E-1	55,000 - 381.9	105,000 - 729.1	Comp. 838 Ten. 197	At 110,000 lbs., diagonal cracks appeared on end sur- faces. Ultimate load 125,000 lbs.
19 thru 22	E-2	39,000 - 270.8	108,000 - 750.	Comp. 758 Ten. 181	Vertical crack reached front surface at 60,000 lbs. Upper diagonal crack 114,000 lbs. Ultimate load 126,000 lbs.
23 thru 24	E-3	45,000 - 312.5	106,000 - 736.1	Comp. 1956 Ten. 250	
25 & 26	3/4 E-1	39,000 - 270.8	65,000 - 451.38	Comp. 964 Ten. 177	
27 thru 29	3/4 E-2	54,000 - 375.0	94,000 - 652.8	Comp. 1400 Ten. 193	At 70,000 lbs. surface cracks appeared, somewhat below the failure surface on the interior of the specimen. Ultimate load 75,000 lbs.
30 thru 32	3/4 E-3	33,000 - 229.1	74,000 - 513.8	Comp. 417 Ten. 125	

^xExcept where noted, ultimate load was not appreciably higher.

*Free Field Stress

1
1
1

PHOTOGRAPHS

1st.
62,400 #

62,400

FIG. 1



FIG. 2

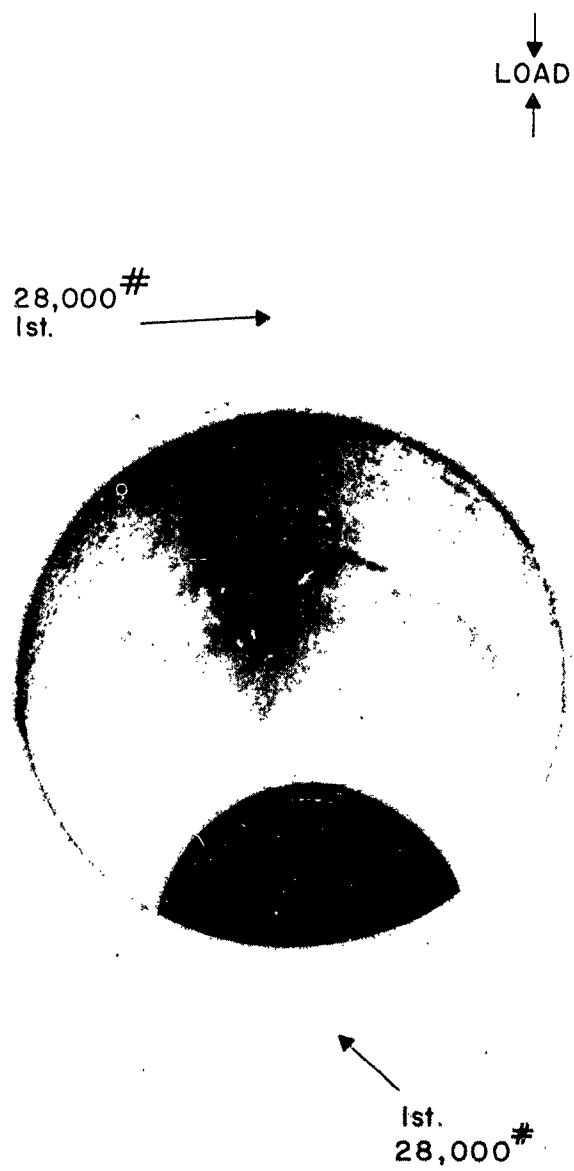


FIG. 3

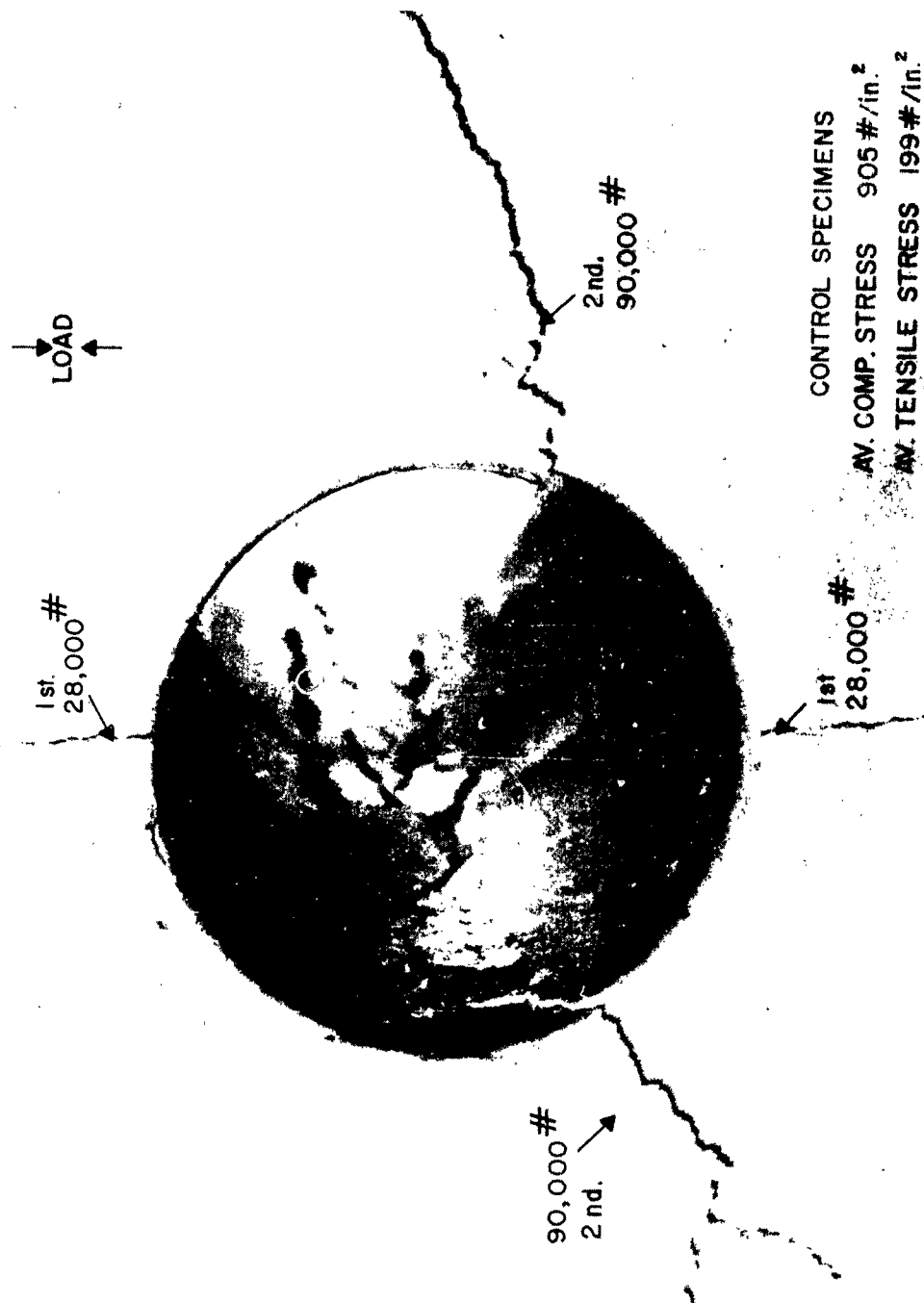


FIG. 4

LOAD

ST.
65,000#

14
65,000#

FIG. 5



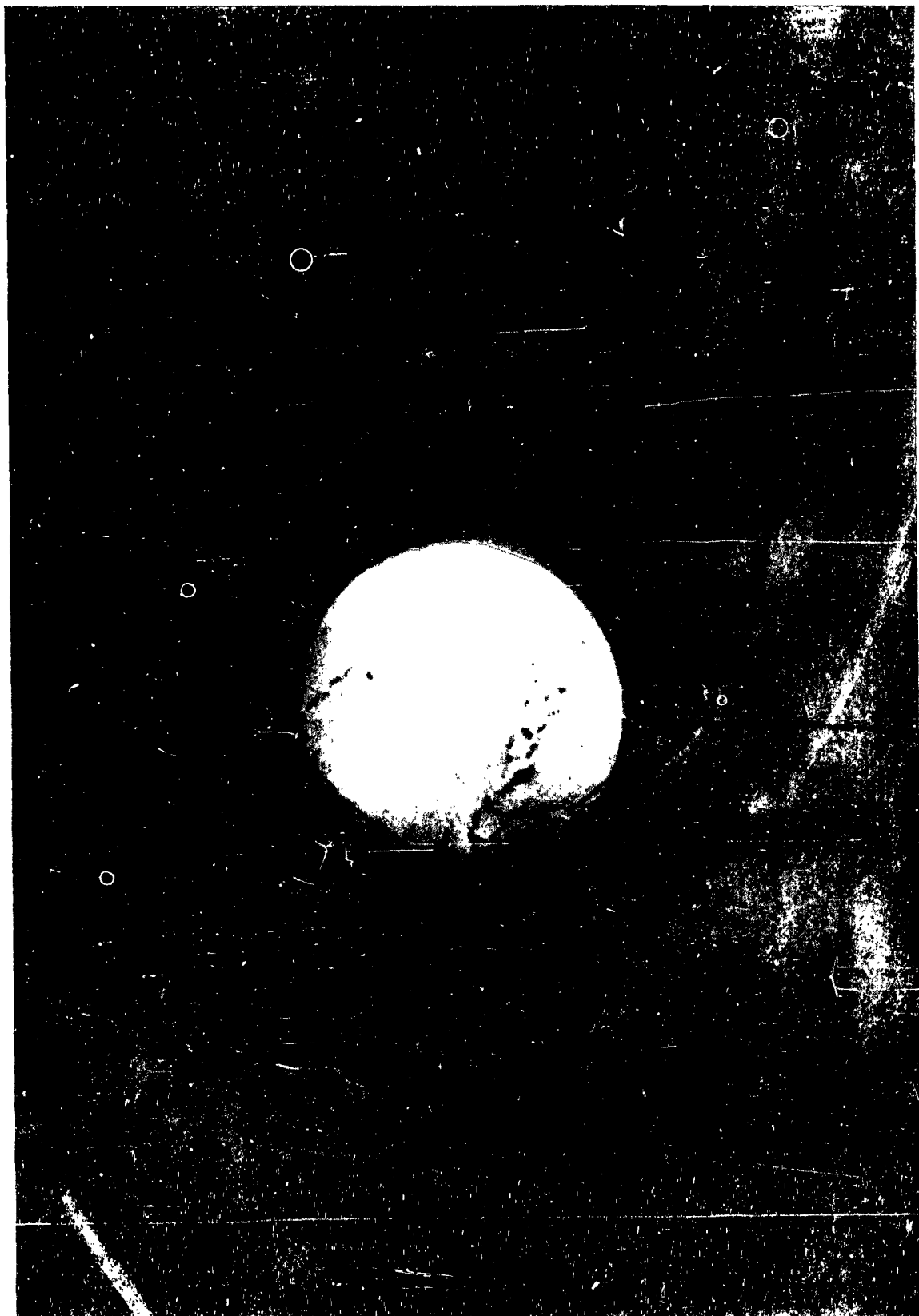


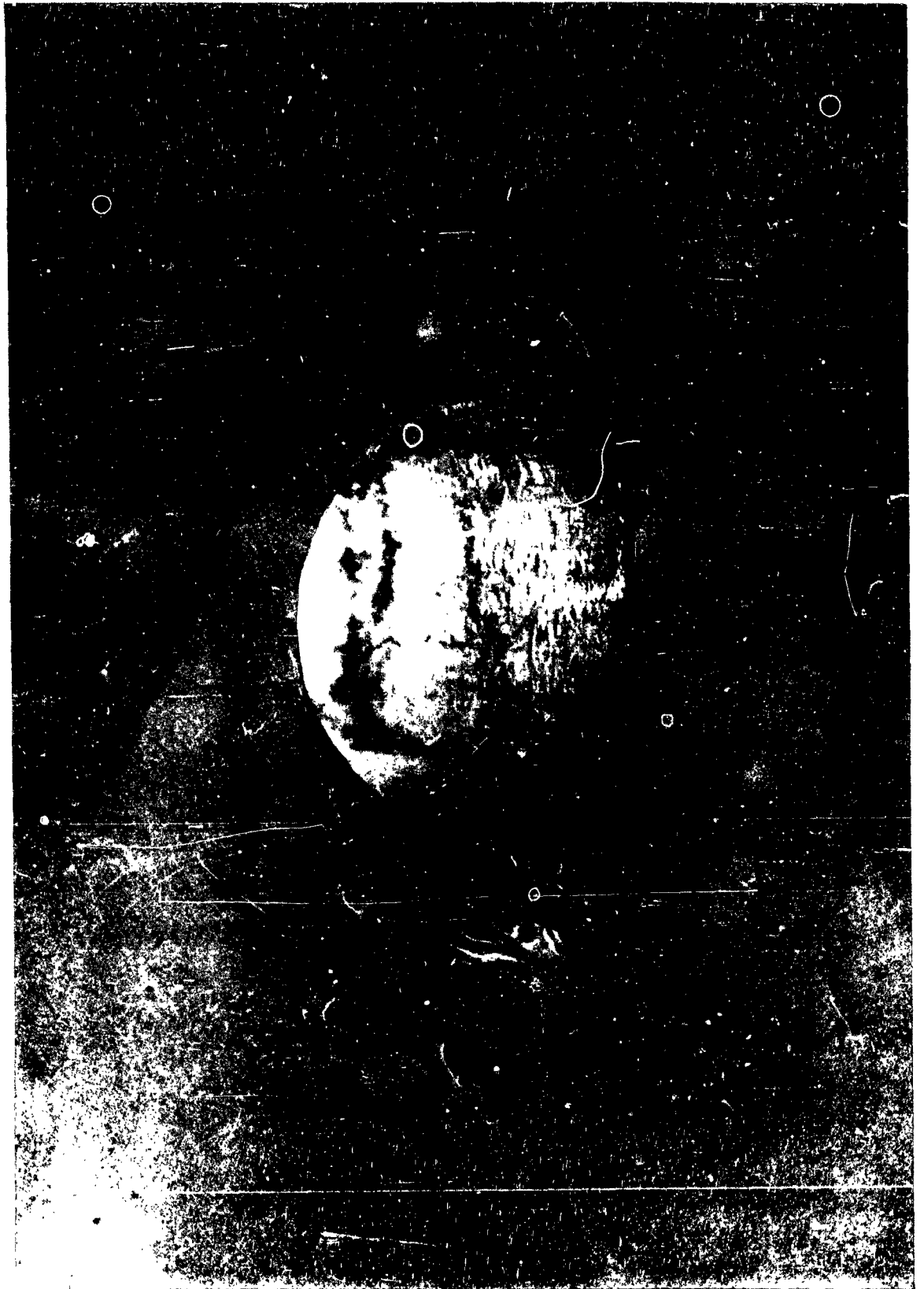
LOAD

1st 56,000

1st 56,000

FIG. 7







$\frac{3}{4}$ C-2

LOAD

ST.
60,000



$\frac{3}{4}$ C-2

LOAD

ST.

60,000*

ND

11,900*

3/4 C-3

LOAD

1st.
22,000 #



1st.
22,000 #

FIG. 13

3C-3
4

LOAD

1st.
22,000 #

2nd.
24,000 #

1st.
22,000 #

2nd.
24,000 #

CONTROL SPECIMENS
AV. COMP. STRESS 1141 #/in²
AV. TENSILE STRESS 201 #/in²

FIG. 14

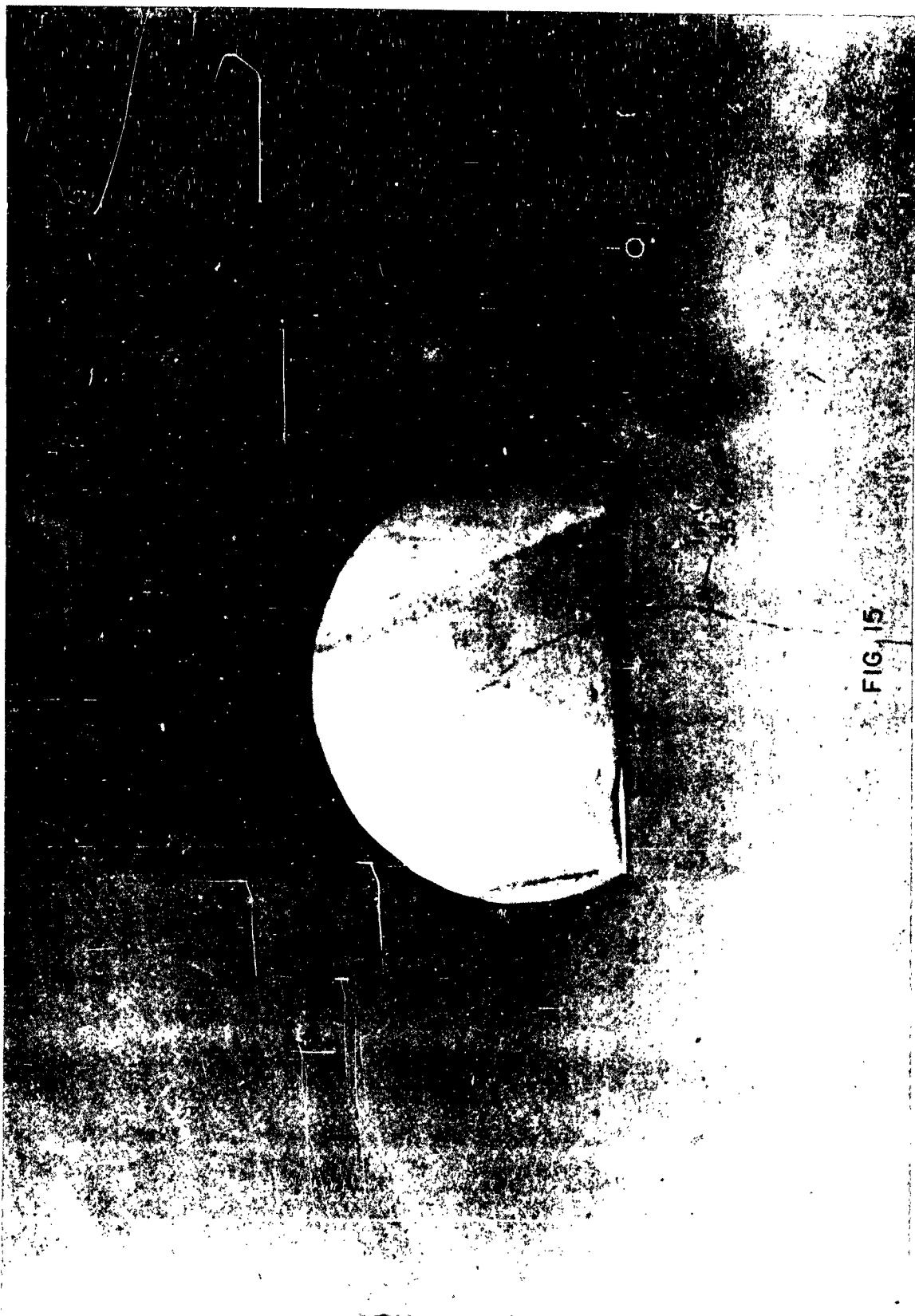


FIG 15

C-4

1st.
35,000 #

35,000 #

CONTROL SPECIMENS

AV. COMP. STRESS 822 #/in²

AV. TENSILE STRESS 228 #/in²

35,000 #

35,000 #

2nd

E-1

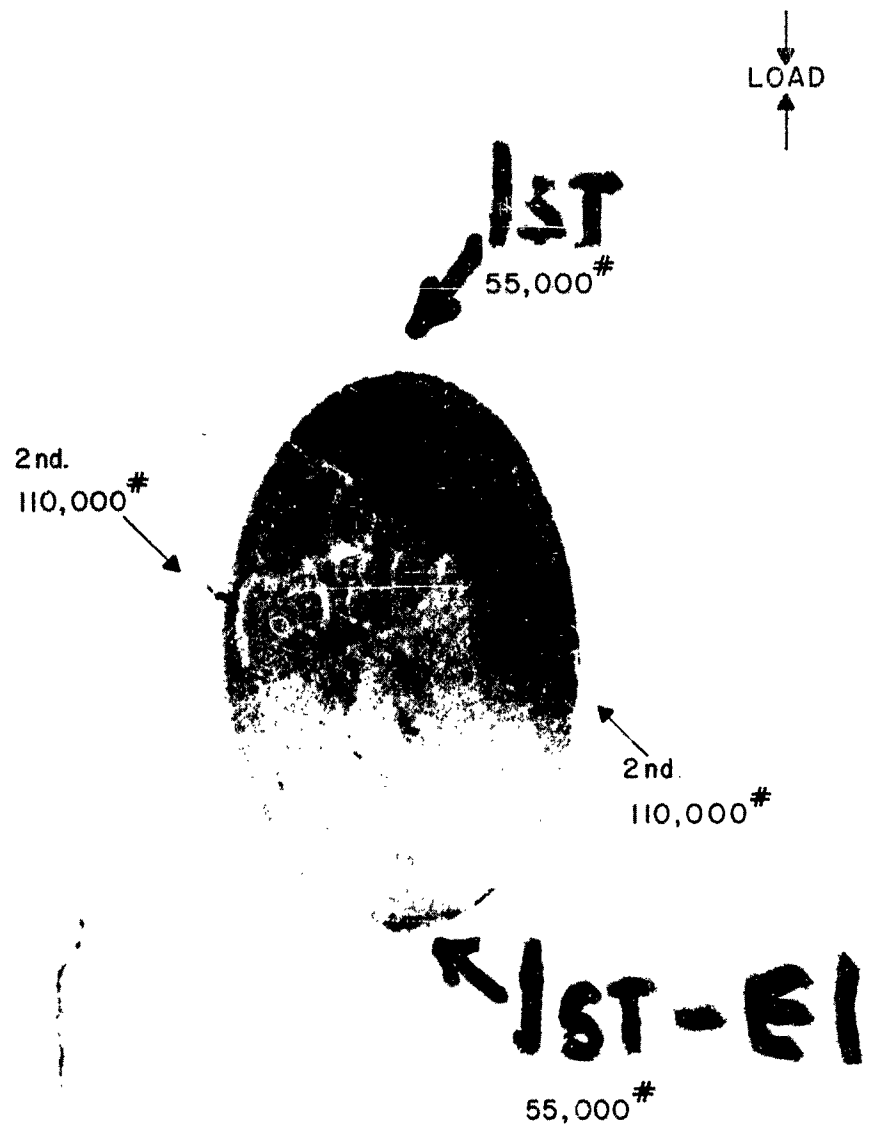
LOAD

1 st.
55,000#



1 st.
55,000#

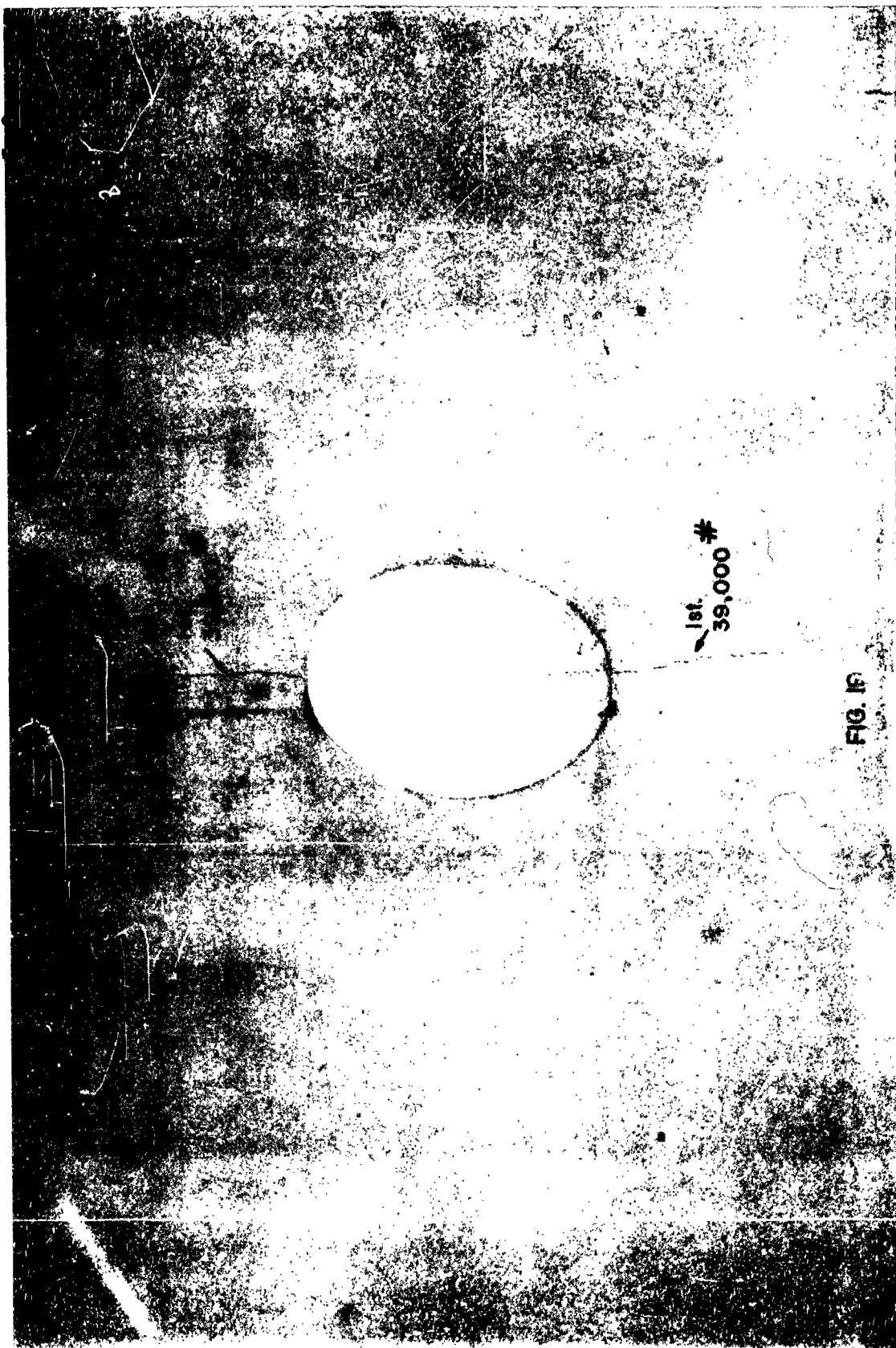
FIG.17



CONTROL SPECIMENS

AV. COMP. STRESS 838 #/in²
 AV. TENSILE STRESS 197 #/in²

FIG. 18







CONTROL SPECIMENS

AV. COMPRESSIVE STRESS 765 #/sq

AV. TENSILE STRESS 101 #/sq

39,000

FIG. 11

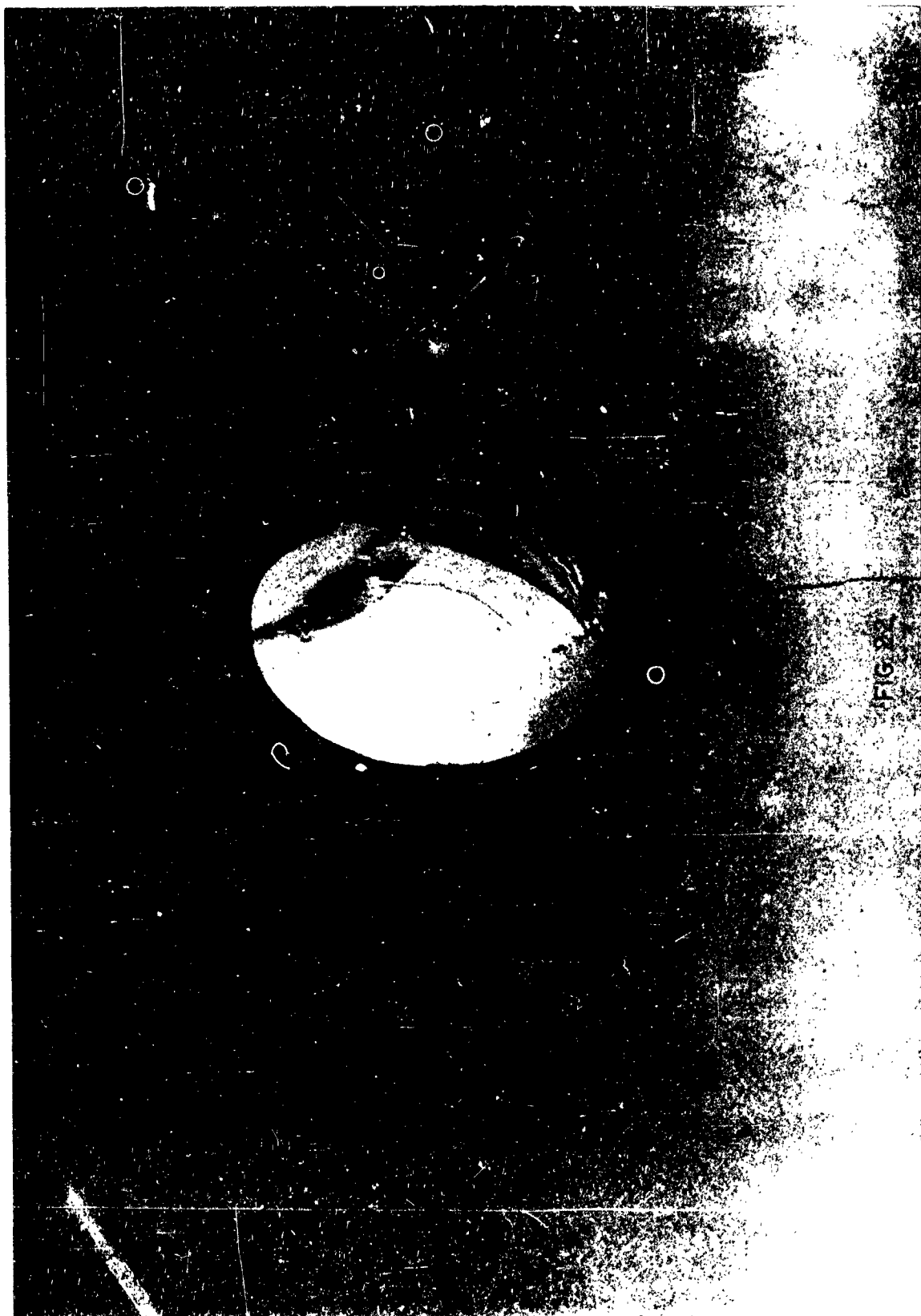


FIG. 22

E-3

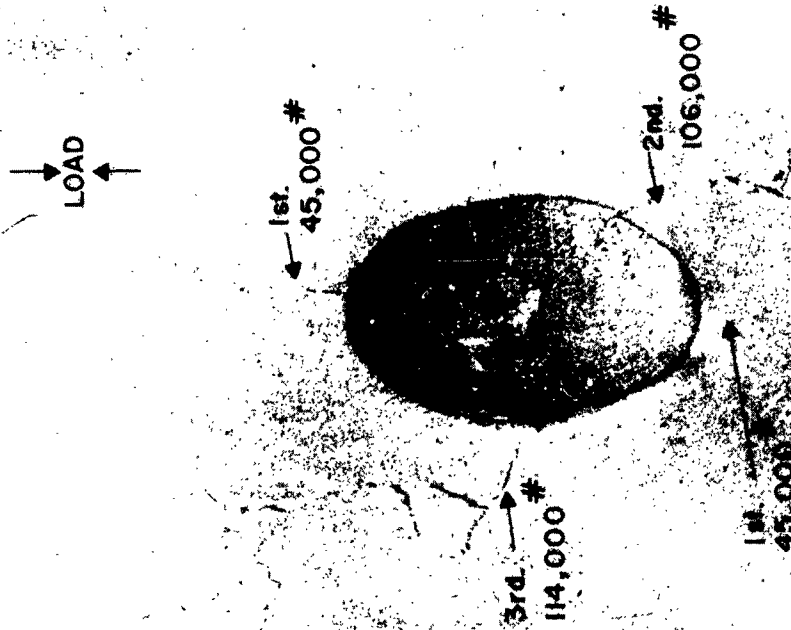
LOAD

1st.
45,000 #



1st
45,000 #

FIG. 23



CONTROL SPECIMENS
 AV. COMP. STRESS 1956 #/in²
 AV. TENSILE STRESS 250 #/in²

FIG. 24

$$\frac{3}{4} E - I$$

↓
LOAD
↑



ST.

39,000 #

ST.

39,000 #

FIG. 25

3
4 E-1

↓
LOAD
↑



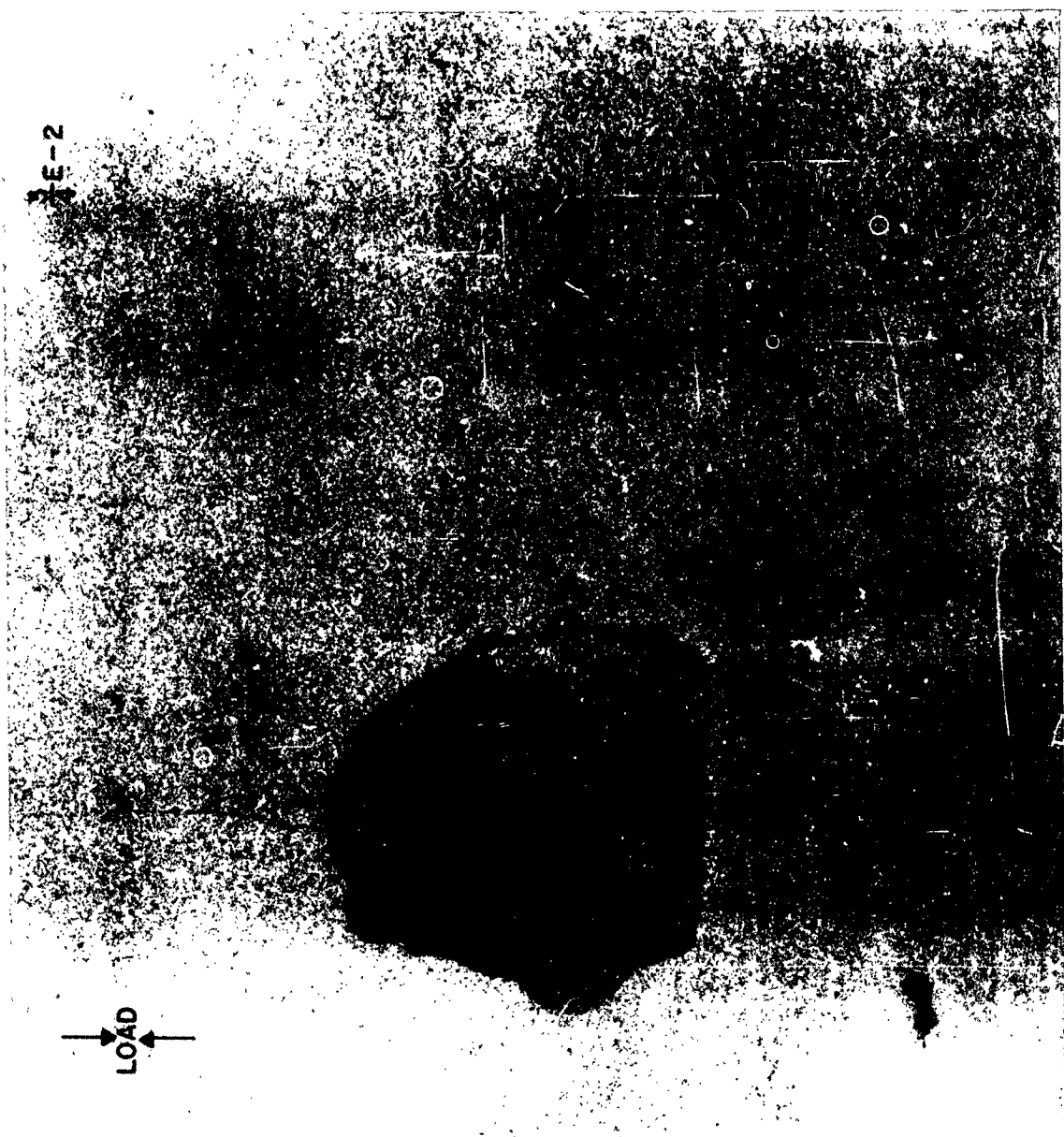
ST.
39,000#



3

Fig. 2

LOAD



$\frac{3}{4}$ E-2

↓
LOAD
↑

1st.
54,000 #



1st.
54,000 #

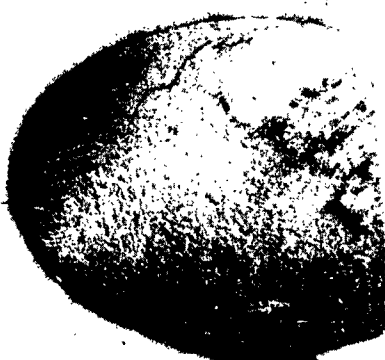
FIG. 28

$\frac{3}{4} E-2$

LOAD

1st. 54,000 #

2nd. 94,000 #

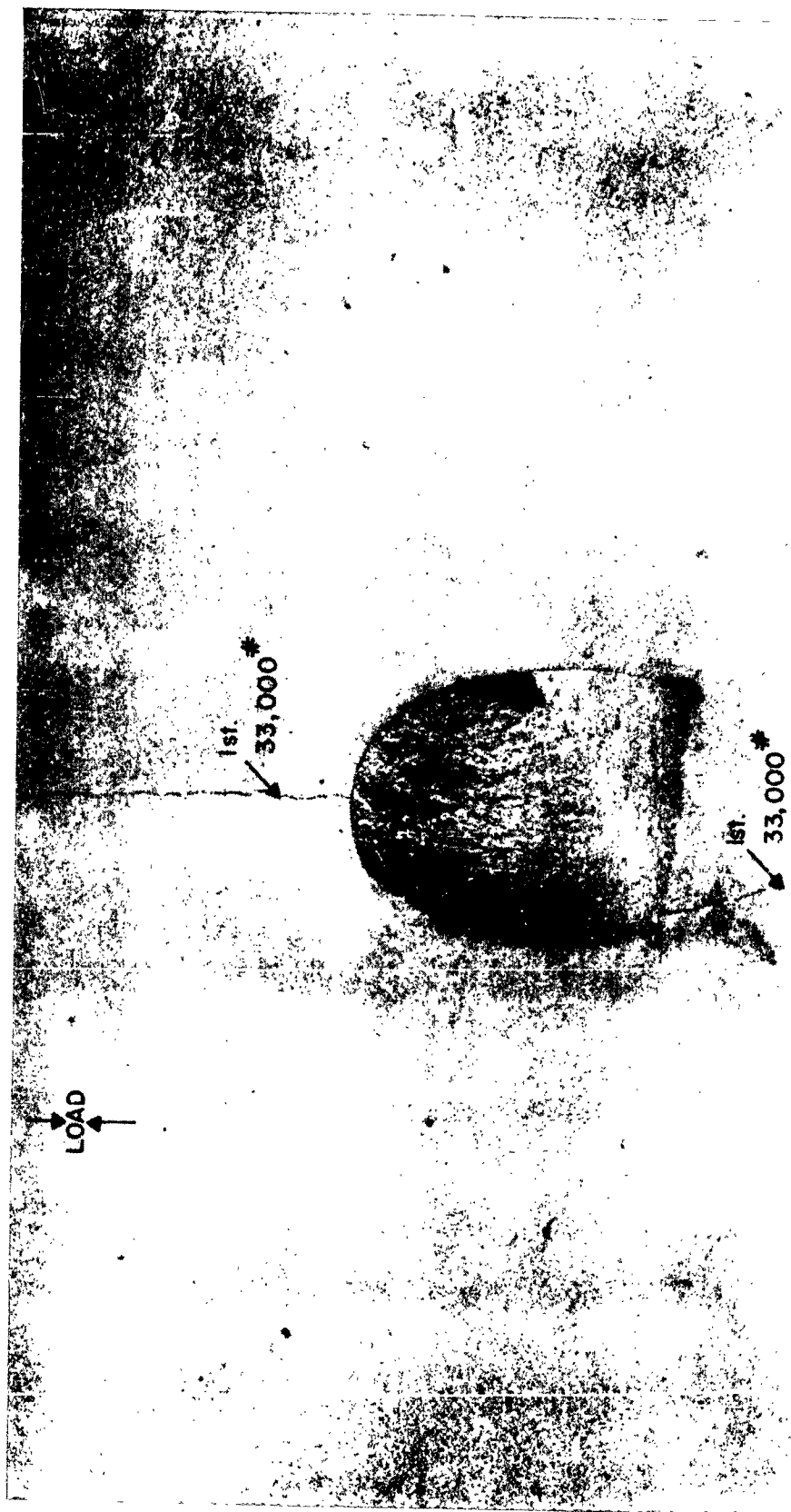


2nd. 94,000 #

1st. 54,000 #

CONTROL SPECIMENS
AV. COMP. STRESS 1400 #/in²
AV. TENSILE STRESS 193 #/in²

FIG. 29



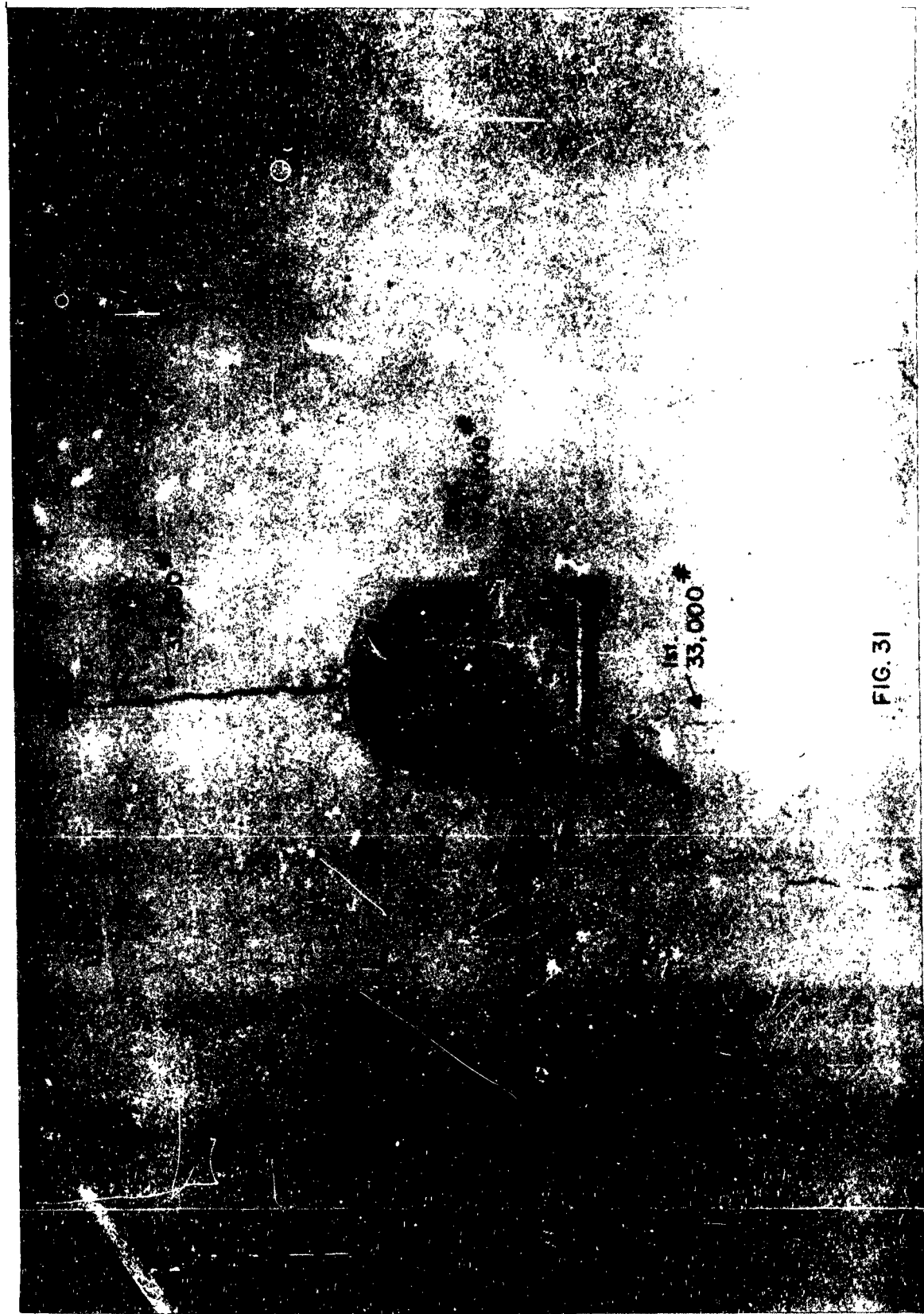


FIG. 31

AV. COMP. STRESS 417
AV. TENSILE STRESS 12547/in

FIG. 32

5.0 DISCUSSION OF RESULTS

In making general observations on the basis of the foregoing results, there is first of all a strong and obvious consistency of basic mechanism of failure. The first cracks to appear are always in a vertical plane. These undoubtedly correspond to the maximum tensile stress in the body (see Section 5), and to the fact that the tensile strength is so much lower than the compressive strength. Examination of the surfaces of these cracks and comparison with the failure surfaces of the sample cubes substantiate this conclusion. The cracks usually did not progress more than half way to the top or bottom, and sometimes they were forced closed as the load increased.

The second failure mechanism is also essentially the same for all the specimens tested, it seems to consist of slip or shear along planes inclined about 35° to 40° to the vertical and passing through the ends of the minor axis of the cylindrical hole. There are four possible planes for this slippage. It is conceivable that slip could take place along all of them producing four wedges, the top and bottom ones moving together and the side wedges being forced apart. The "shear wedges" usually observed within the holes indicate that this probably did occur in the vicinity of the holes, but full cracks never developed in all four places in a single specimen. The most frequent mechanism was for opposite planes to form resulting in a diagonal surface from corner to corner, intersecting the hole (actually the surfaces turned toward the loaded ends as they progressed from the hole), but in some specimens (e.g. C-3) two upper surfaces formed in conjunction with the lower vertical crack to form a Y-shaped fracture surface system.

In addition to the consistency among specimens of the two basic fracture mechanisms, it should be noted that the two stage failure was repeated in every case, and caused complete failure.

In some instances (e.g. 3/4 E-1) the photographs can be somewhat misleading with respect to the location of the shear fracture surface, because the crack appearing on the end at the specimen does not coincide with the location of the main shear surface on the interior. In the case of specimen 3/4 E-1 the crack on end is up to two and one half inches below the shear surface two inches back in the specimen.

It seems justified to make a quantitative comparison of the strengths of the shapes, based on the load required for the first and second modes of fracture and the ultimate load supported, and modified by a consideration of the control sample data. On the basis of such a comparison the following ranking was obtained by the writer.

<u>1st Fracture Mode</u>	<u>2nd Fracture Mode</u>
C	E
E	C
3/4 E	3/4 E
3/4 C	3/4 C

To a certain extent these rankings can be understood by an elastic analysis (sec. 6), for example, the second mode and the ultimate strength are to a large extent dependent on shear and compressive stress concentration and the ellipse is clearly superior on these grounds, whereas in tensile stress concentration and thus the first mode, they are equal. Also the three-quarter shapes can be expected to be weaker than the smoother full shapes and the 3/4 ellipse stronger than the 3/4 circle since the interior angle associated with the latter is somewhat more acute.

The scatter of various strengths within a particular specimen type cannot be traced to the control strength variations alone, indeed it is hard to correlate them at all in some instances. The possibility of dirty equipment, which is known to have a marked effect on strength, can probably be discounted because the care used would certainly have eliminated large particles of foreign matter, and a dispersion of small particles or a chemical in solution would have effected the control samples as well as the specimen. The explanation seems rather to lie in the realm of statistical variations and size effect, but as this consideration is of a rather conjectural nature, it is deferred until Section 6.

6.0 CONCLUSION

As mentioned in Section 5, analysis of the test situation by homogeneous, isotropic, linear elasticity yields results which are in accord

with some aspects of the observed mechanisms. If the body is considered to be an unlimited body in a state of plane strain under a uniform uniaxial compressive stress $-P$, the stresses can be found very simply, particularly for points on the surface of the hole⁽⁷⁾. The results for the circular hole are a maximum tensile stress $\sigma_{\theta\theta} = P$ at the top and bottom of the hole, and a maximum compressive stress of $\sigma_{\theta\theta} = -3P$ at the ends of the horizontal diameter, with the shear stress zero on the hole but at a maximum with respect to θ on the 45° planes in the interior. Similarly for the ellipse, for a major to minor axis ratio of $1\frac{1}{2}$ to 1, the maximum tensile stress occurs at the top and bottom and is P , the maximum compressive stress is at the ends of the minor diameter, but its value is only $-7/3 P$, the shear stress is also less severe. Values of the maximum stresses around $3/4$ circle and ellipse cavities are given in MITRE's SR-36.⁽⁸⁾ These values support first the observed tension mode of failure, the tensile strength of samples being always less than one third of the compressive strength. If the analysis can be continued after the tensile cracks have formed, the second mode of failure also is consistent with the elastic analysis, and furthermore, the greater strength of the ellipse is predicted.

As stated in the discussion of the test results, the scatter of quantitative results for a particular specimen and between specimens (to whatever extent any such comparison is justified) is greater than seems reasonable from a consideration of mix procedure, control sample data, and test procedure. This seems particularly true in view of the generally good agreement as to mechanism of failure. Considered from the viewpoint taken in the study of fracture mechanics and strength-theory for brittle materials since the publication of Griffith's fundamental paper⁽⁹⁾, the scatter becomes less disturbing. From this point of view, plaster is a heterogeneous material containing a random dispersion of flaws in the form of voids left by the evaporation of the excess water remaining after complete hydration of calcium sulfate to form $2\text{CaSO}_4 \times \text{H}_2\text{O}$. Failure will occur locally whenever the resultant stress at some such flaw exceeds the strength of the surrounding material; if the combination of stress level and flaw characteristics in the vicinity is sufficient to provide the necessary energy for rupture, a crack will propagate. The analysis is thus inherently statistical, con-

cerned in part with the distribution of flaws sufficiently severe to cause failure at a particular stress level. The resulting conclusion concerning the scatter in quantitative results of fracture tests is not only that a scatter is to be expected, but that the larger the specimens tested, the greater the expected scatter (this because with a greater volume comes an increased probability of encountering a critical flaw in an area of maximum stress). Thus, the relatively small variance in control sample data compared to that for the test specimens (which contain roughly 180 times the volume) seems to some extent expectable on statistical grounds.⁽¹⁰⁾⁽¹¹⁾

As was pointed out earlier in this report, the stress distribution around a circular cavity under dynamic loading is approximately the same as in the static case. Therefore, it is not surprising to find that the modes of failure obtained in this report are similar to those obtained under dynamic loading.⁽²⁾ In view of this, it seems reasonable to assume that for elastic rock media where the ratio of compressive strength to tensile strength is greater than 10, and where the ratio of compressive strength to shear strength is greater than 2, the sequence of occurrence of cavity failure mode will be tensile then shear. Examples of rock that satisfy this criterion are granite, limestone, sandstone and marble.

A few words of caution are in order: first, because of the inherent statistical scatter that occurs in this type of test, it would be desirable to accomplish more tests of this nature; perhaps using actual rock as a test material. Secondly, one of the most difficult problems in the experiment of this nature is the scaling affect. It is not known how one scales a finite model such as those used in a laboratory to an actual site in a semi-infinite medium. Care must be taken to insure that edge effects are not introduced into the experiment; hence alter the stress distribution around the cavity and causing failures that do not represent the actual failure of a deep underground cavity. It is to be noted, however, the dimensions of the casted cube used in this test are 6 times greater than the dimensions of the cavity. Furthermore, in all the cases, fracture occurs throughout the entire length of the hole. This is an indication of a two dimensional failure, however, in order to be sure we suggest further work along this line to be carried out, perhaps using bigger cast cube or testing the cube under a confined configuration.

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